

# SIMULATION OF THE DUCTILE DAMAGE DURING THE METAL FORMING

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## Abstract

It was shown in this paper that the damage degree is estimated by the scalar value  $\omega$ , that is equal to 0 ( $\omega = 0$ ) before plastically strain and is equal to 1 ( $\omega = 1$ ) at the macrocracks moment. There are two criteria that describe micro damage. The value  $\omega = \omega_*$  corresponds to the generation of micro voids that couldn't be recovered by recrystallization but do not reduce the metal strength. The value  $\omega = \omega_*$  corresponds to the generation of micro voids that reduce the metal strength and material longlife. The models of metal damage accumulation during pure and alternate forming also the model of metal damage recovery under the recrystallization are developed. The specimen testing at high loading parameters gives the basic equations of the ductile damage mechanics. All of that gives the method to study ductile damage during the metal forming.

## 1 INTRODUCTION

A moment of metal damage is usually conditioned with the reach of critical values of load  $P = P_*$ , stress  $\sigma = \sigma_*$ , effective shear strain  $\Lambda = \Lambda_*$ . On the right parts of these equations there are empirical characteristics of material and on the left part there are certain operators which characterize the load process. Deformation criterion  $\Lambda = \Lambda_*$  is widely used for analyses of metal damage under metal forming [1, 2]. The fault of such method is that the critical values ( $P_*$ ,  $\sigma_*$ ,  $\Lambda_*$ ) are not constants but depend on strain conditions [2, 3]. Experiments of P. Bridgman show the relation between  $\Lambda_*$  and hydrostatic pressure, and experiments of S. Manson allow to establish the influence of the amplitude of the alternate strain  $\Lambda_i$  on a critical value  $\Lambda_*$ . Sometimes it is established that ductility of the materials is increased if the formation of new micro voids can be stopped or diminished [4]. A development of the mechanics of metal damage can be related with a ductility diagram [5]. This method was applied in the proceedings [6, 7] by the creation of the metal damage accumulation models under the pure and alternate strain, the defect recovery model under the recrystallization and testing of the given models at the various load conditions of the specimens.

## 2 MODELS OF THE METAL DAMAGE ACCUMULATION AND RECOVERY

### 2.1 Model of metal damage accumulation under the pure forming

To study the metal damage accumulation during the metal forming a conception of defect free body is used where  $\omega = 0$ . It corresponds to the beginning of the plastic strain when  $\tau = 0$ . The metal damage rate  $d\omega/d\Lambda$  is equal to 0 at  $\tau = 0$ . The value  $\Lambda$  is an effective shear strain which the material particle accumulates moving along its trajectory:

$$\Lambda = \int_0^t H d\tau; \quad (1)$$

$H$  is an effective shear strain rate

$$H = (2e_{ij}e_{ij})^{1/2}, \quad (2)$$

where  $e_{ij}$  – are the deviatoric strain rate components. At the moment of macro cracking ( $\tau = t_f$ ) metal damage  $\omega$

is equal 1 ( $\omega = 1$ ) and metal damage rate  $d\omega/d\Lambda$  is inversely to the limited ductility  $\Lambda_f$  (the effective shear strain of the pure strained specimen at the constant values of mechanical parameters):

$$\frac{d\omega}{d\Lambda} = \frac{a}{\Lambda_f}, \quad (3)$$

where  $a$  and  $\Lambda_f$  are empirical functions which characterize properties of strained material depending on the stress parameters  $\sigma/T$  and  $\mu_\sigma$ ,  $\sigma$  is a middle normal stress,  $T$  is effective shear stress:

$$T = \left( \frac{1}{2} s_{ij} s_{ij} \right)^{1/2}, \quad (4)$$

where  $s_{ij}$  are the deviatoric stress components and  $\mu_\sigma$  is the Lode's parameter:

$$\mu_\sigma = \frac{3s_{22}}{s_{11} - s_{33}}. \quad (5)$$

At the random moment ( $\tau = t$ ) the metal damage rate is equal

$$\frac{d\omega}{d\Lambda} = \frac{a\Lambda^{a-1}}{\Lambda_f^a}. \quad (6)$$

The relationship  $\Lambda_f(\sigma/T)$  at certain constant values of  $\mu_\sigma$  is shown in fig.1.

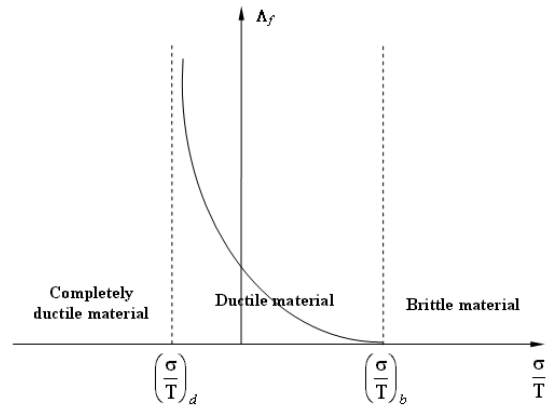


Fig.1. Diagram of the limited ductility

Fig.1 distinctly shows the specific areas of material behavior such as brittle fracture where  $\sigma/T > (\sigma/T)_b$ ; ductile fracture where  $(\sigma/T)_d < \sigma/T < (\sigma/T)_b$ ; the area of the unlimited ductility  $\sigma/T < (\sigma/T)_d$  where

the recovery of volumetric defects prevails ( $\Lambda_f \rightarrow \infty$ ). While estimating the Lode's parameter  $\mu_\sigma$  influence on the ductility diagram  $\Lambda_f(\sigma/T)$  we use the specimens tests under the axial symmetric tension ( $\mu_\sigma = -1$ ), flat forming ( $\mu_\sigma = 0$ ) and the axial symmetric compression ( $\mu_\sigma = 1$ ). The parameter  $\sigma/T$  is set constant by controlling the pressure  $p$  in the testing chamber according to a certain law. It is possible to approximate the limited ductility diagram with the equation below:

$$\Lambda_f = \exp \left[ b_1 + b_2 \mu_\sigma + (b_3 + b_4 \mu_\sigma) \frac{\sigma}{T} \right], \quad (7)$$

where  $b_1, b_2, b_3, b_4$  are material constants.

## 2.2 Model of metal damage accumulation during a alternate forming

The most of the metal forming processes have alternate forming which consists of several ( $n$ ) stages of pure forming. The metal damage at the end of  $i$ -th stage and at the beginning of the  $(i + 1)$ -th stage are equal. The metal damage rate ( $d\omega/d\Lambda$ ) at the beginning of each stage decreases to zero. So after  $n$  stages of alternate forming the metal damage can be found with the following equation:

$$\omega = \sum_{i=1}^n \int_0^{\Lambda_i} \frac{a \Lambda^{a-1}}{\Lambda_p^a} d\Lambda, \quad (8)$$

where  $\Lambda_i$  is the amplitude of alternate forming at the  $i$ -th stage. The function  $a(\sigma/T)$  is determined by means of specimen tests for alternate torsion where  $\sigma/T$  is constant during each test. The equation below approximates test results:

$$a = a_0^{1+c \frac{\sigma}{T}}, \quad (9)$$

where  $a_0$  and  $c$  are material constants.

## 2.3 Model of metal damage recovery under the recrystallization

It is known that during the recrystallization a new core structure is formed and the defects recover. However, a volumetric defects just reduce their sizes and still remain in the metal. The value of residual metal damage  $\omega_0 = \omega - \Delta\omega$  determines its influence on metal strength and longlife. The metal damage recovery diagram  $\Delta\omega(\omega)$  is shown in fig.2.

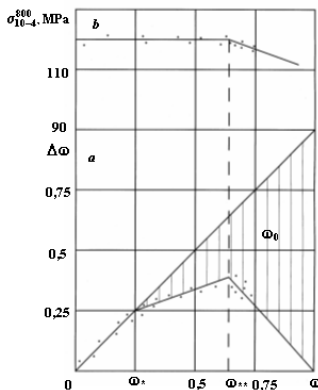


Fig. 2. Diagram of the metal damage recovering (a) and metal strength decrease by micro voids and micro cracks

The diagram shows that all the deformation defects recover after the recrystallization in the area  $0 < \omega < \omega_*$ . In the area  $\omega_* < \omega < \omega_{**}$  the deformation defects remain in the metal after the recrystallization however the strength characteristics do not reduce. If  $\omega_{**} < \omega < 1$  then the value  $\Delta\omega \ll \omega$  and the residual metal damage  $\omega_0 \rightarrow \omega$  thus the metal strength reduces. So it is possible to introduce two criteria of the metal micro damage in order to analyze the metal forming processes:  $\omega = \omega_*$  and  $\omega = \omega_{**}$ .

## 3 DUCTILE CRACK DEVELOPMENT

Let the macrocrack at the initial moment has the length  $2c_0$  with a curve on the radius  $r_0$ . Let's consider a defect deformation during flat forming. The defect perimeter does not reduce but the radius either increases or decreases thus defect dimensions can be defined as  $2c$  and  $r$  at the instant moment. Stress and strain conditions along the front of the defect development for ideal-ductile material are defined as  $T = \tau_s$ . In the polar coordinate system  $(\rho, \varphi)$  on the free forces surface  $\sigma_{\rho\rho}|_{\rho=r} = 0$  then  $\sigma_{\varphi\varphi} = \pm 2\tau_s$ ;  $\sigma_{zz} = \pm \tau_s$ . The stress sign is defined from physical point of view that stress is positive if the defect radius increases and it is negative if defect radius decreases. The radial equilibrium equation is

$$\frac{d\sigma_{\rho\rho}}{d\rho} + \frac{\sigma_{\rho\rho} - \sigma_{\varphi\varphi}}{\rho} = 0. \quad (10)$$

The Mises's equation is

$$\sigma_{11} - \sigma_{33} = 2\tau_s. \quad (11)$$

Resolving (10) and (11) equations together the stress parameters can be determined:  $\mu_\sigma = 0$ ; and  $\sigma/T$  is

$$\frac{\sigma}{T} = \left( \pm 1 + 2 \ln \frac{\rho}{r} \right). \quad (12)$$

There is a radial metal flow at the defect area when  $v_\varphi = 0$ . A radial strain component can be determined by solving the uncompressive material equation

$$\frac{dv_\rho}{d\rho} + \frac{v_\rho}{\rho} = 0 \quad (13)$$

with satisfaction of boundary condition  $v_\rho|_{\rho=r} = \pm v_0 = \text{const}$  and defect radius can be determined as follows  $r = r_0 \pm v_0 \tau$ . At the moment  $\tau = t$  we have  $v_\rho = \pm v_0 \cdot r/\rho$ . Thus the effective shear strain rate can be determined as

$$H = 2v_0 \frac{r}{\rho^2}. \quad (14)$$

The maximum value  $H_{\max} = 2v_0/r$  is at the peak of the crack. Fig.3 shows a slip-lines field at the peak of the crack and the relations between the parameters  $\sigma/T$ ,  $H/H_{\max}$  and coordinate  $\rho$ .

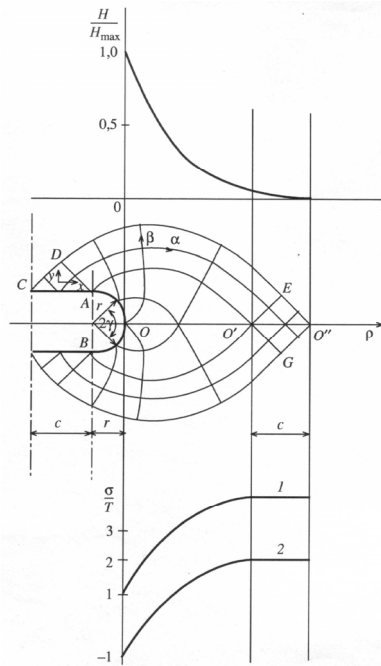


Fig. 3. The slip-line field, stress parameter  $\sigma/T$  and effective shear strain rate at the defect area

The relation between the effective shear strain and coordinate  $\rho$  can be found as

$$\Lambda = \left| 2 \frac{r_1^2}{\rho^2} \ln \frac{r_1}{r_0} \right|, \quad (15)$$

where  $r_0$  and  $r_1$  are the values of defect radius before and after the forming.

Fig.4 shows various ways of defect development bound up with the metal damage. At the front of crack development the metal damage accumulation takes place and at the moment  $\omega = 1$  a new crack is formed with the radius  $r'_0$ :  $a$  – for the crack which is transformed to a void,  $b$  – for the void which is transformed to a crack. If the defect radius reduces under the deformation and  $(\sigma/T)_d > 2,14$  then the crack closes and recovery occurs.

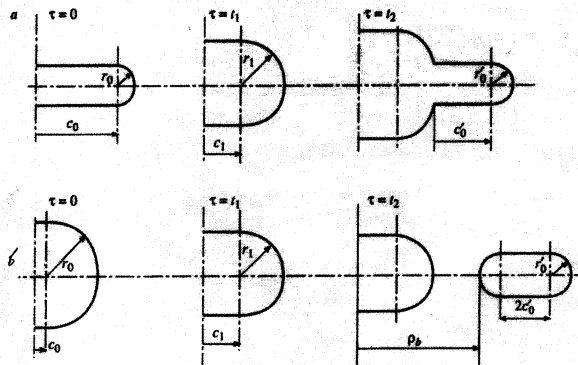


Fig. 4. The scheme of two ways of defect development bound up with metal damage

#### 4. PHYSICAL MODELLING OF METAL DAMAGE

The metal damage accumulation in the material particle at the actual metal forming process can be substituted for the specimen test if similarity criteria are satisfied at each instant. The similarity  $(\mu_\sigma)_n = (\mu_\sigma)_m$  can be satisfied by choosing the proper specimen test mode. For the axial symmetric forming ( $\mu_\sigma = -1$ ) the tensile tests of the cylindrical specimens with the neck or with the soft layer are recommended. For the flat forming processes ( $\mu_\sigma = 0$ ) the torsion, tensile and bending tests of flat specimens are recommended. If necessary notches of various shapes can be utilized. For the axial symmetric compression processes ( $\mu_\sigma = 1$ ) the plastic bend of thin plates with the high pressure liquid through the round die is suitable. While performing the specimen test in the chamber with liquid pressure control the similarity  $(\sigma/T)_n = (\sigma/T)_m$  is satisfied. The effective shear strain in the testing specimen must be the same as in the given metal forming process ( $\Lambda_m = \Lambda_n$ ). Besides the similarity criteria  $\Lambda_i = idem, n = idem$  must be satisfied for the alternate strain. Found by equation

$$\omega = \sum_{j=1}^K \left[ \sum_{i=1}^n \int_0^{\Lambda_i} \frac{\Lambda^{a-1} d\Lambda}{\Lambda_f^a} - \Delta\omega_j \right], \quad (16)$$

where  $n_i$  is the number of alternate forming stages;

$\Delta\omega_j$  is the metal damage reduction under recrystallization at the  $j$ -th cycle of plastic and heat processing;  $K$  is the number of cycles of metal damage at the actual metal forming process as well as it is equal in specimen test ( $\omega_m = \omega_n$ ). This can be provided in case that the same chemical and phase consistency as well as the metal structure and the scale factor including are available. The advantage of the physical modeling of metal damage is that actually any of the cold metal forming processes mode can be reproduced by the specimen test in the chamber with high load parameters controlling [7]. The metal damage identification after the cold forming or after the cold forming and annealing is carried out when examining the specimen fracture in further tests. In those tests the strained specimen having deformation defects is subjected to brittle fracture influenced by the stress concentrator, low temperature and dynamic load. The fig.5 shows ductile damage tracks as the volumetric micro voids and micro cracks at the background of the brittle fracture.

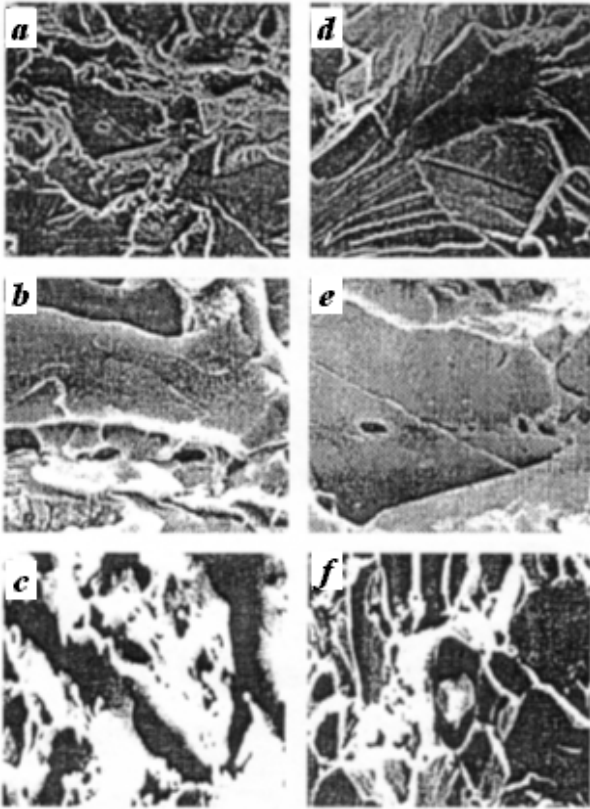


Fig. 5. The cold strain voids (a, b, c) and voids after annealing (d, e, f):  $\omega < \omega_*$  (a, d);  $\omega_* < \omega < \omega_{**}$  (b, e);  $\omega > \omega_{**}$  (c, f)

These tracks show the residual metal damage level after realization of the various specimen test programs.

## 5. TECHNIQUE AND EQUIPMENT FOR MODELLING

Physical modeling of metal damage during metal forming is accomplished by means of testing a specimen at special machines having a chamber of high pressure. The pressure in the testing chamber increase up to 1000 MPa and the temperature rises up to 1150 °C. The temperature during testing is held to be constant and pressure in that chamber is controlled by a certain law according to changes of the parameter  $(\sigma/T)_n$  along the trajectory of its movement at actual metal forming process. It is shown in fig.6 that the scheme of testing machine have a chamber of high pressure.

The main feature and its advantage appears to be that specimen (9) fixed between the lower plunger (10) and the container (8) can be affected by independent and controllable load parameters such as pressure of operating liquid  $p$ , speeds of axial transfer of the container and rotation of the lower plunger. As it was mentioned above the way of testing and the specimen configuration are defined by the type of metal forming process. For example, wire drawing process has  $\mu_\sigma \approx -1$ . The appropriate way of modeling is thought to be tension of cylindrical specimens. At thin sheet rolling where  $\mu_\sigma \approx 0$  the torsion of cylindrical specimen and strain of a flat one can be used as modeling testing. When axial symmetrical sheet stamping is going where  $\mu_\sigma \approx 1$ , then compression of cylindrical specimen or

plastic bend of thin plate by high pressure liquid through round or elliptic die can be used as modeling testing. To keep the experimental parameters constant  $(\sigma/T) = (\sigma/T)_* = const$  which is necessary for making a ductility diagram  $\Lambda_j(\sigma/T)$  the pressure should be controlled according to a defined law. The load factors for the tensile case (17), for the torsion (18), for the plastic bend (19) are:

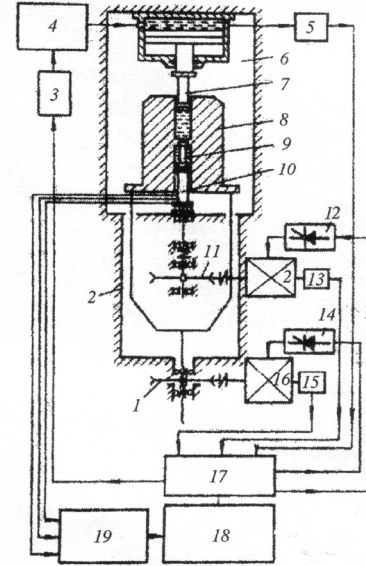


Fig.6. The scheme of testing machine with the high loading parameters chamber

$$P = \left\{ \frac{1}{\sqrt{3}} \left[ 1 + \frac{3}{4} (\Lambda - 0,2)^{0,81} - \frac{1}{\sqrt{3}} \left( \frac{\sigma}{T} \right)_* \right] \right\} (\sigma_{0,2} + g\Lambda^b), \quad (17)$$

$$P = -\frac{1}{\sqrt{3}} \left( \frac{\sigma}{T} \right)_* \cdot (\sigma_{0,2} + g\Lambda^b), \quad (18)$$

$$P = -\frac{1}{\sqrt{3}} (\sigma_{0,2} + g\Lambda^b) \cdot \left[ (m+1)/\sqrt{m^2 + m + 1} - \left( \frac{\sigma}{T} \right)_* \right], \quad (19)$$

where  $(\sigma/T)_*$  is given from the conditions of the experiment,  $m = b/a$  is axis relation of the ellipsis like die,  $g$  and  $b$  are empirical coefficients which characterize specimen material strengthening.

## 6. CONCLUSIONS

The models of nucleation and the grow of the ductile metal damage during pure and alternate forming as well as the metal damage recovery models, criteria of micro and macro damage supposed to give the methodology of metal forming analyses. The method and equipment of physical modelling of metal damage is proposed. During modelling it is possible to solve the problems which are important for theory and technology development, the metal structure and properties improvement, formation of strained texture and operating characteristics of metal production. The method of physical modelling of the various metal forming processes can be performed by the universal testing machine having the high specimens load parameters.

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